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Memo: Distro "A" only.

MEMORANDUM FOR PRS (In-House Publication)

FROM: PROI (STINFO)

25 Apr 2003

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-VG-2003-110**
J. Michael Fife and Andrew Ketsdever (AFRL/PRSS), "Overview of Micropropulsion Research Activities at the AFRL Rocket Propulsion Directorate"

DARPA Meeting
(Dulles, VA, 6-7 May 2003) (Deadline: 24 Apr 2003 – PAST DUE)

(Statement A)

DARPA Workshop

Micro-Thruster Technology for Military Applications

Dulles, VA; May 6-7, 2003

Sponsor: Dr. John D. Evans
Program Manager
Microsystems Technology Office

Background/Motivation

Evolving military doctrine continues to impose ever-more-stressing requirements for greater range and enhanced maneuverability of miniature satellites (picosats, 1-10 kg), micro-unmanned air vehicles (UAVs), sensor systems, projectiles, and missiles. To meet these requirements, continuing advances in micro-thruster technology are needed to increase thrust, fuel efficiency, thruster/system controllability, system deployability, and to reduce system weight. Flexible/adaptable micro-thruster technologies that enable on-mission trade-offs between features (e.g., fuel efficiency and thrust) are also of growing interest.

Potential space applications for micro-thrusters include picosat station-keeping and formation flying for communications and radar applications, rapid (days) or slow (weeks) on-orbit satellite inspection and repair, strike-from-orbit weapons, satellite active protection, and satellite decoys. Potential terrestrial application for micro-thrusters include precise emplacement of unattended ground sensors (UGS); precise emplacement of "tags on mobile enemy platforms; sensor field reconfiguration; decoy deployment; active protection systems for ground combat vehicles; void suppression for supersonic projectiles; subsonic, non-lethal, and decelerating projectiles; lofted and other smart/brilliant munitions; and UAV propulsion and control. Potential marine applications for micro-thrusters include ship self-defense, decoy deployment, super-cavitating projectiles and sensors, and micro-unmanned underwater vehicle (UUV) propulsion and control.

Relevant thruster technologies include but are not necessarily limited to solid propellant, liquid propellant, hybrid liquid/solid systems, cold gas thrusters, pulsed plasma thruster, laser sublimation thrusters, ion drives, and other types that may be identified. Such thrusters may be used either as the primary system or component propulsion source, or for guidance. Total propulsion system masses (exclusive of propellants) are envisioned to range from several tens of grams to several kilograms, with comparably sized payloads.

Workshop Objectives: (1) To review and discuss recent developments and current state-of-the art with respect to micro-thruster technologies; (2) To assess prospects for accelerated advances in the area given an intensified focus and appropriate resources; and (3) To identify, the most promising potential applications of the technology in both military and non-military systems.

Specific Goals

- To discuss key mission requirements for current and potential future military applications of micro-thrusters, and to define micro thruster performance parameters critical to meeting these requirements;
- To assess the ability of current micro-thruster technologies to meet current and projected future military requirements, and to identify important applications and missions that might be significantly enhanced or enabled by further developments in the area;
- To identify critical technical challenges associated with the development of advanced high-performance micro thrusters, and the most plausible approaches for overcoming recognized challenges;
- To define suitable performance metrics and establish realistic goals for next-generation micro thrusters that must be achieved for new developmental efforts in this area to be considered successful;
- To identify the most essential elements of a possible focused new effort to develop high-performance micro-thrusters able to establish the feasibility of new or significantly improved micro-thruster technologies in the near term (12-18 months), and leading to significant laboratory demonstrations of militarily important components/systems within the next 3-5 years.

As part of this workshop, participants will be expected to directly contribute to collective realization of these goals by either (1) developing a brief mission requirements analysis for a potential micro-thruster mission, or (2) developing a brief micro-thruster capabilities analysis for a current or potential micro-thruster technology. Further details regarding these analyses will be included in the workshop letter of invitation.

JDE/WES
April 7, 2003

Overview of Micropropulsion Research Activities at the Air Force Research Laboratory Propulsion Directorate

6-7 May, 2003

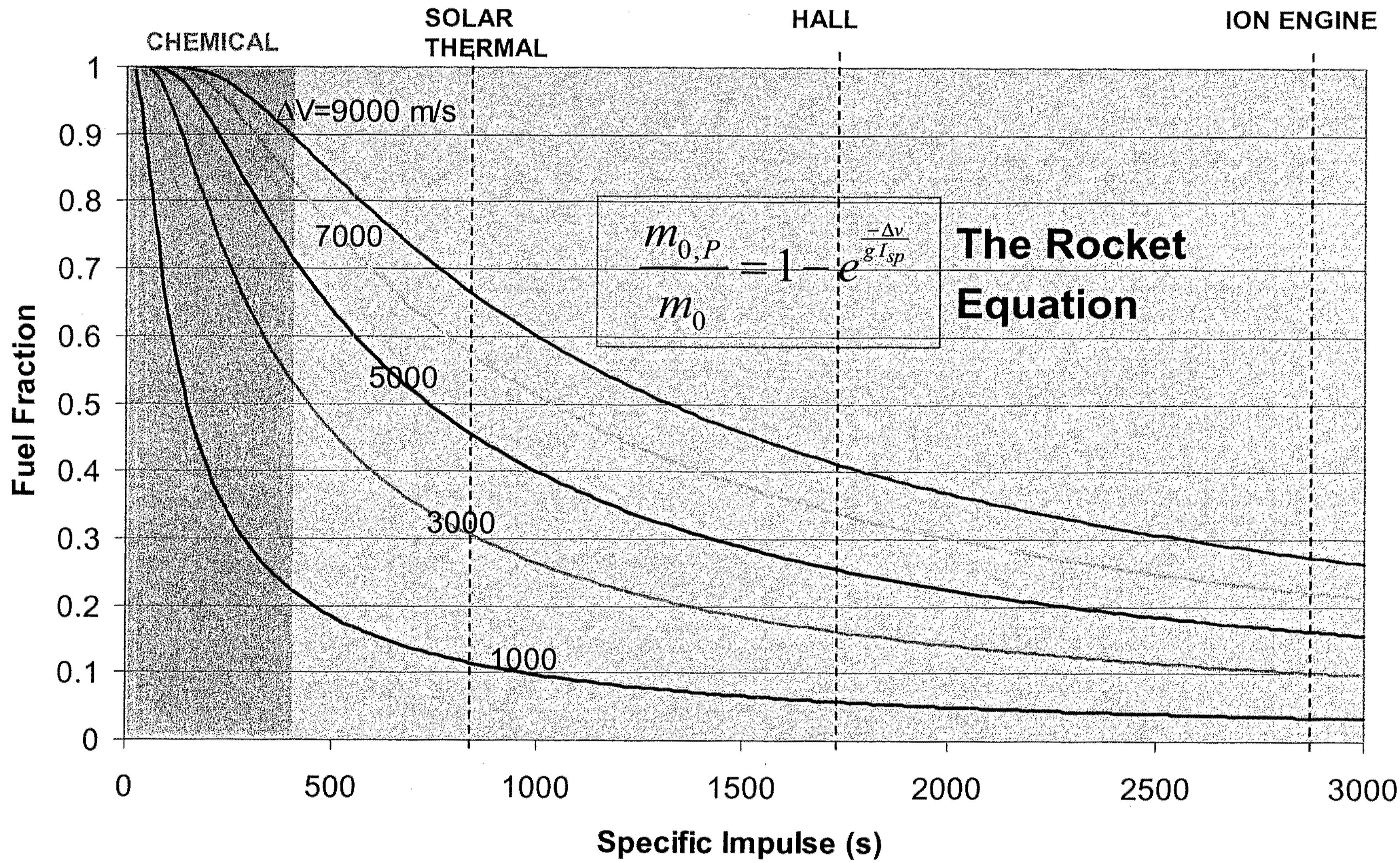
J. Michael Fife, PhD

Andrew Ketsdever, PhD

Space and Missile Division

Domain of Micropropulsion Applicability for DoD Missions

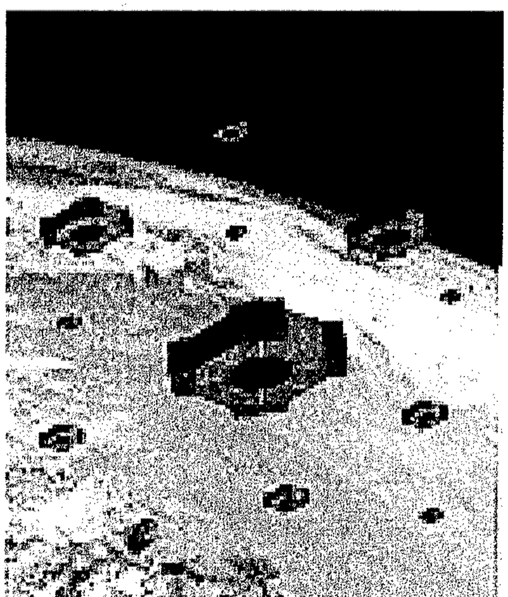
Electric Thrusters for Primary (high ΔV) Spacecraft Propulsion



Solar Electric Microsatellite Propulsion

$$\text{Spacecraft Acceleration} = \frac{\text{Thrust}}{\text{Mass}} \sim \frac{\text{Power}}{\text{Mass}} \sim \frac{\text{Surface Area}}{\text{Mass}} \sim \frac{l^2}{l^3} \sim \frac{1}{l} \qquad (l \equiv \text{Satellite Length})$$

Solar electric propulsion, in general, scales well to reduced sizes.
Chemical propulsion doesn't (mainly for thermodynamic reasons).



Microsatellite Constellation

Chemical

- **High thrust for rapid maneuvering, rapid ACS**
- **Digital MEMS chem thrusters have low I_{bit} for fine ACS, fine positioning**

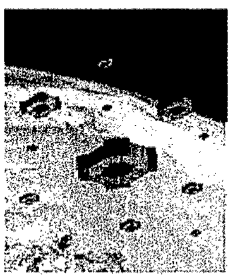
Electric

- **High I_{sp} for fuel-efficient primary propulsion**
- **Low I_{bit} for fine ACS, fine positioning**

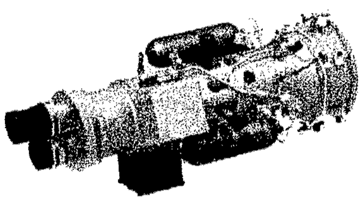
Microsatellite Propulsion Requirements

DoD Microsatellite Missions

On-Orbit Servicing



Formation Flying



Space Control

Propulsion Requirements

Propulsion Requirement	Prop. System Characteristics	Prop. Technologies Being Investigated
High ΔV	High I_{tot}/M_{wet}	μHET Colloid Thruster Arrays* EDT
Fine ACS, Fine Positioning	Low, I_{bit} Predictable I_{bit} Low M_{wet}	μPPT* LPT FMMR μVAT
Rapid ACS, Rapid Maneuvering	High Thrust/M_{dry}	MICRO CHEMICAL THRUSTERS

*show the greatest promise for further miniaturization

Micropropulsion Technology Development Supported by AFRL/PRS

J. Michael Fife, PhD
Leader, Electric Propulsion Group
AFRL/PRSS
Edwards AFB, CA

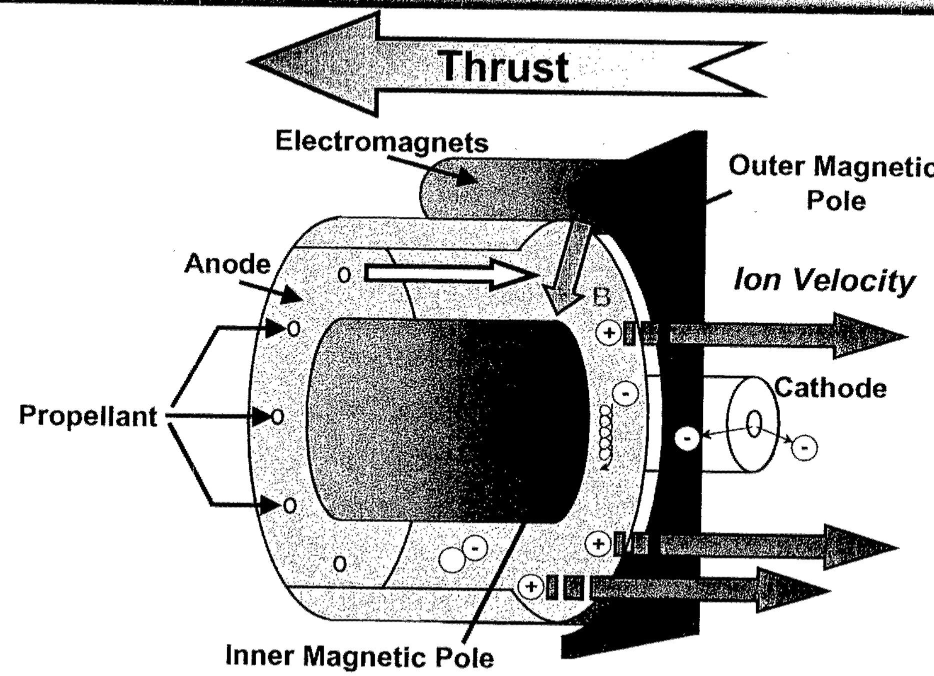
Micro Hall-Effect Thruster (μHET)

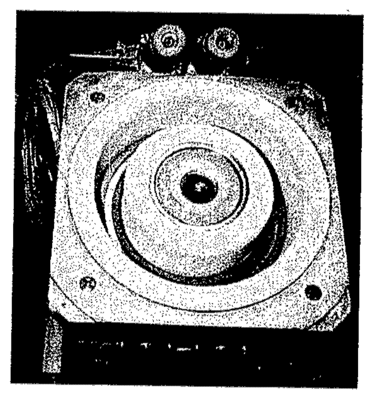
Micro Hall Thruster

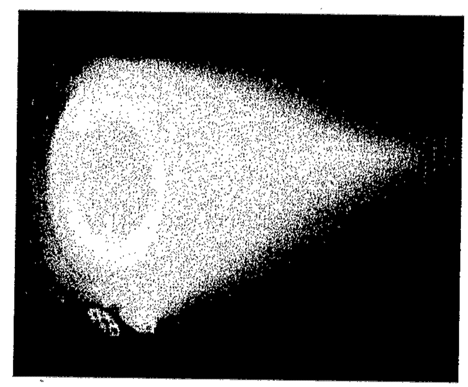
- Principle:
  Electromagnetic Acceleration of Ions
- Propellant: Xe, Kr

Isp = 1000-3000 sec
η = 30-60%
Thrust = 5-400 mN
Power = 50W - 4.5 kW

1. **Electrons emitted from the cathode travel toward the anode.**
2. **Electrons are impeded in the discharge channel by a strong radial magnetic field, causing a strong axial electric field to concentrate in this region.**
4. **This electric field heats the electrons, which subsequently ionize gaseous propellant (xenon) emitted near the anode.**
6. **The ionized gas accelerates axially through the electric field in the discharge channel, exiting the device at high speed, thus producing thrust.**







Stationary Plasma Thruster (Fakel, Kaliningrad, Russia)

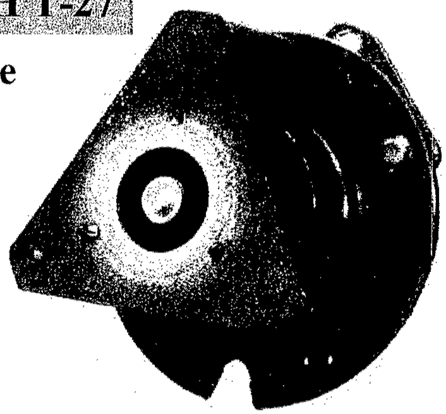
Sub-100W Hall Thrusters

Fakel, Tsnimash – EOARD Funding

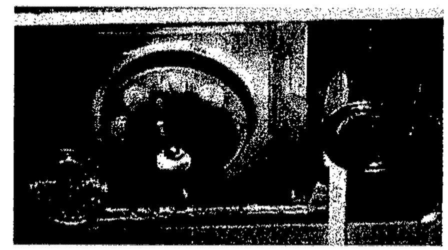
TSNIIMASH T-27

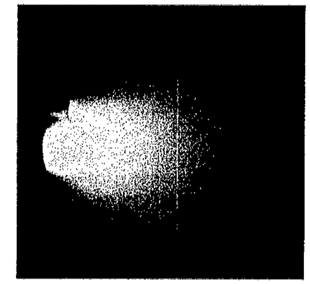
Characterized performance from 40 – 150W
Measure effects of varied:

- Power
- Propellant flow rate
- B field Strength



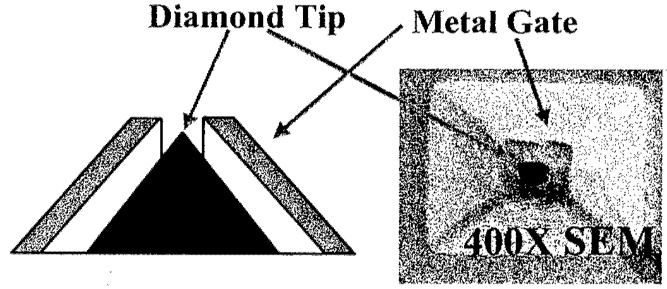
Experimental MIT 50W Hall Thruster

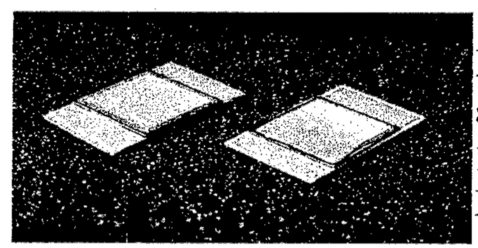




Diamond Field-Emission Cathodes Busek – AFRL Phase II SBIR

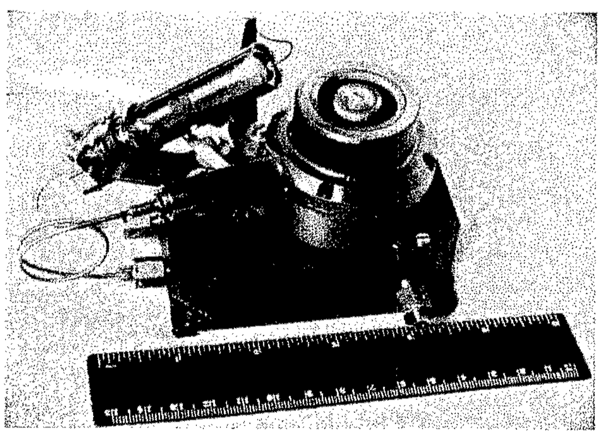
- Low Power , No Propellant





Each 1 cm^2 array has 100,000 Emitters

FAKEL 100W Hall & Miniature Neutralizer



Power = 94.5 W
Thrust = 4.7 mN
Isp = 1000 s
η= 24% (incl. cathode)

Hardware delivered to AFRL

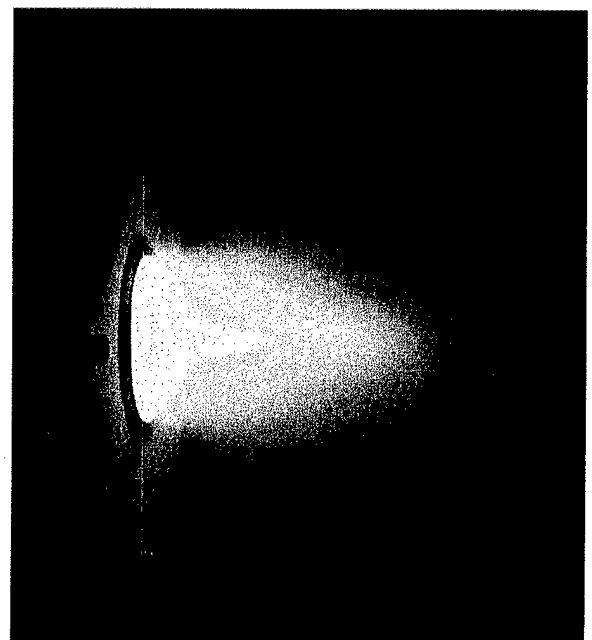
100W Micro-cylindrical Hall thruster

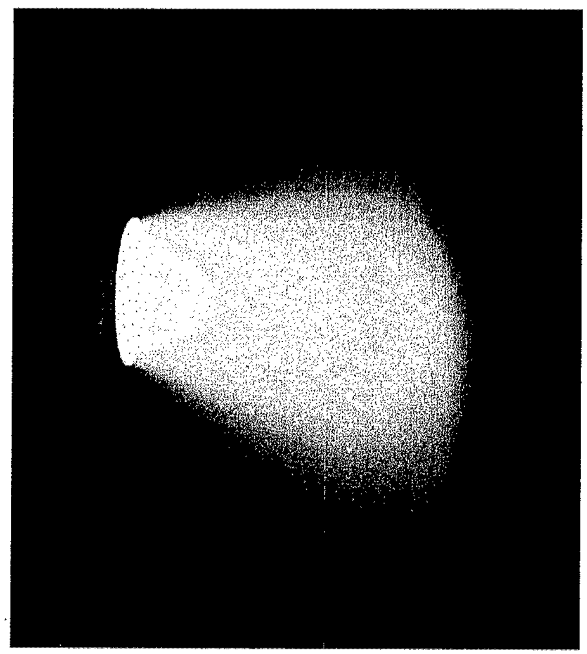
Princeton Plasma Physics Laboratory

Key Features

1. **Efficiency is comparable to annular thruster in the 50--300 W range!**
2. **Ionization efficiency is higher at comparable operating conditions.**
3. **Employs cusp magnetic fields.**
4. **With smaller surface area, fewer inner parts, expect less erosion.**
5. **Operation at lower voltages appears to be feasible.**

Annular
(traditional)

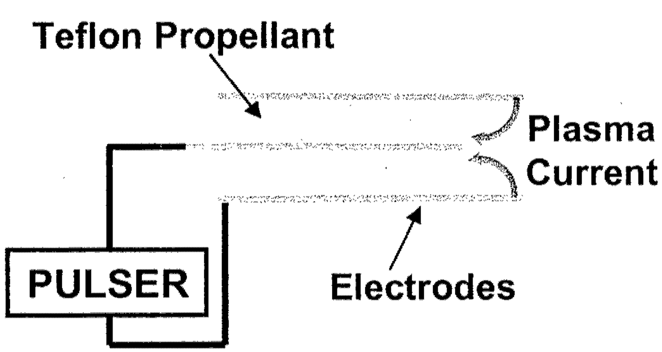


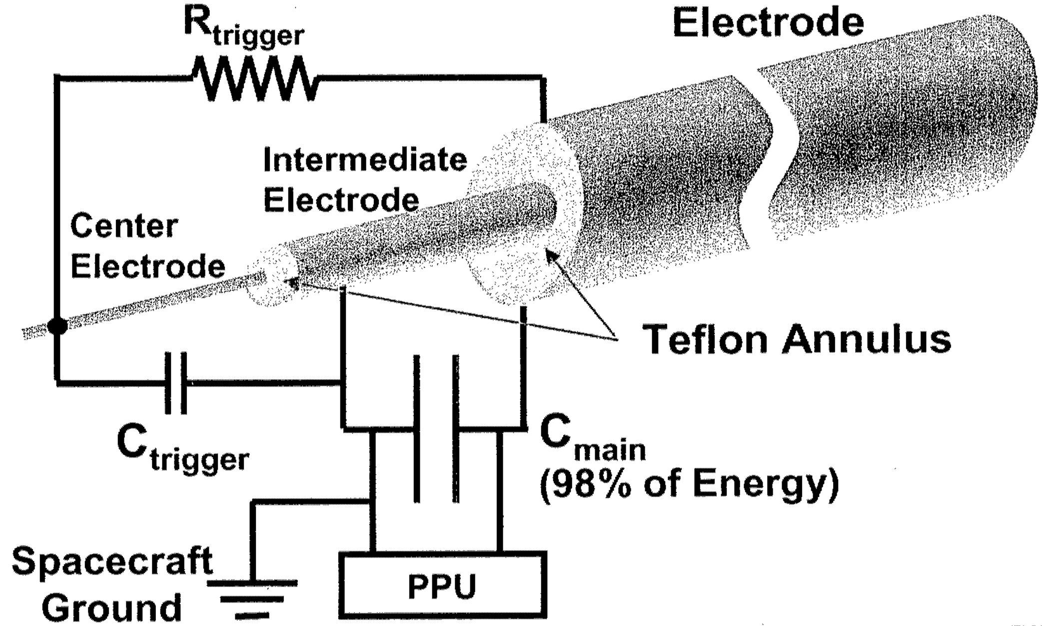


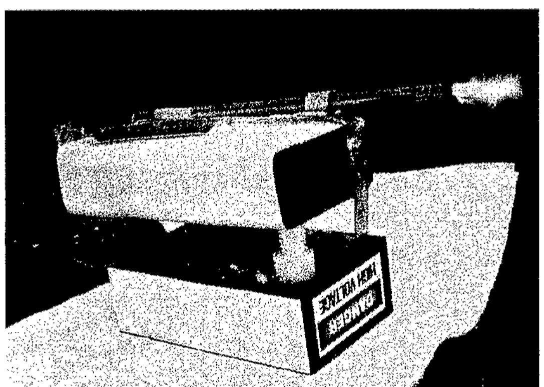
Cylindrical

Micro Pulsed Plasma Thruster (μPPT)

AFRL Micro Pulsed Plasma Thruster

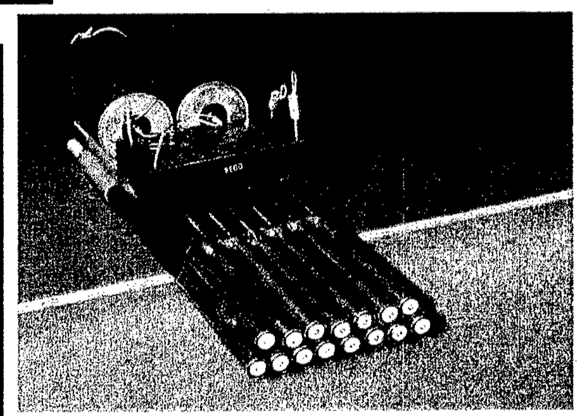






300 gram Lab Model

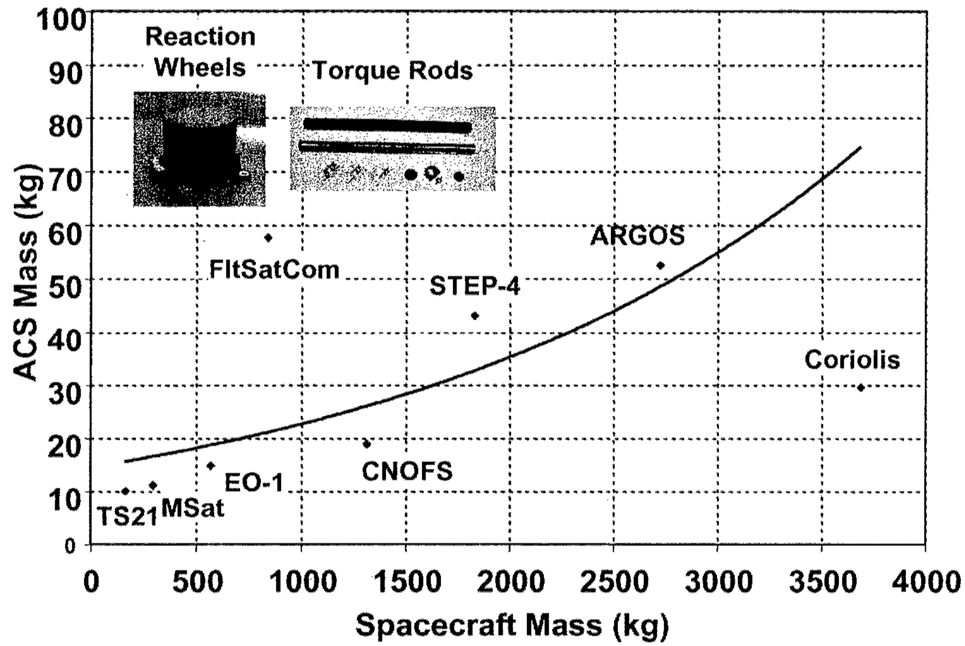
1. Low Dry Mass
2. Demonstrated Long Life:
   - Over 1M shots, 100's hours
   - Limited to propellant avail.
3. Adequate Performance
   - 10 µN/Watt



Multiple-Bar Demo

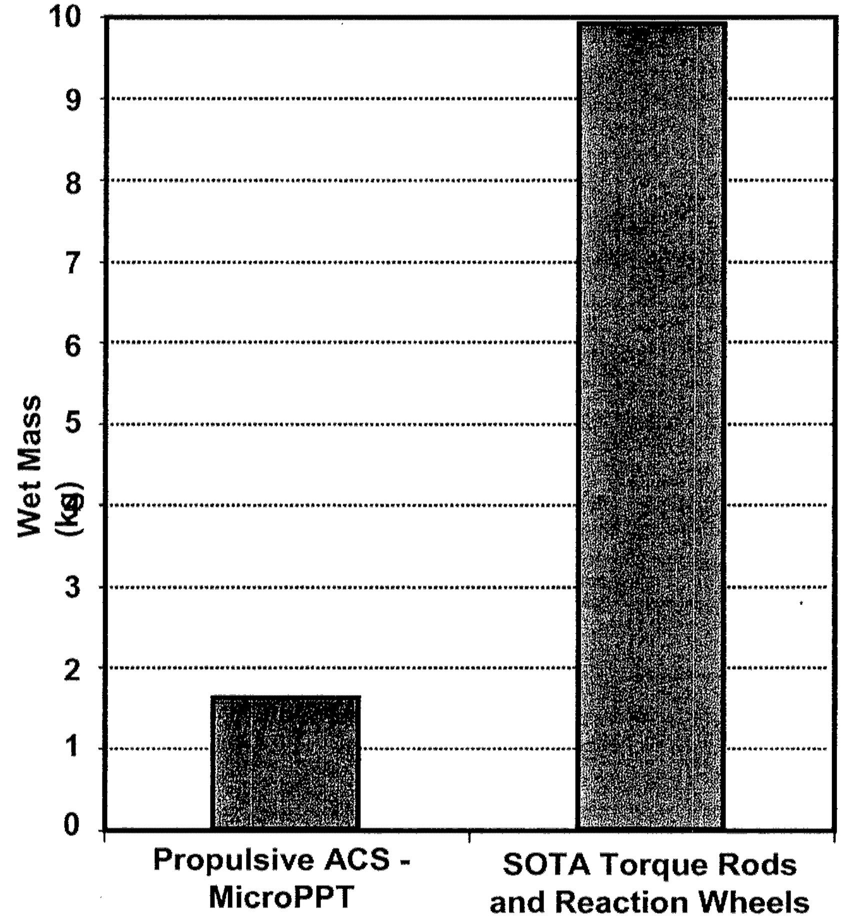
Payoffs to the Warfighter

ACS Mass as a Function of Spacecraft Mass



- Propulsive ACS ~10X less mass
- Additional Payoffs
  - Reduced jitter for imagery (EO-1)
  - 100-1000X Greater pointing accuracy
  - 10X Cheaper, full 3-axis control
  - Dual-use capability

ACS Mass for MicroSat Class Space-Based Radar Mission



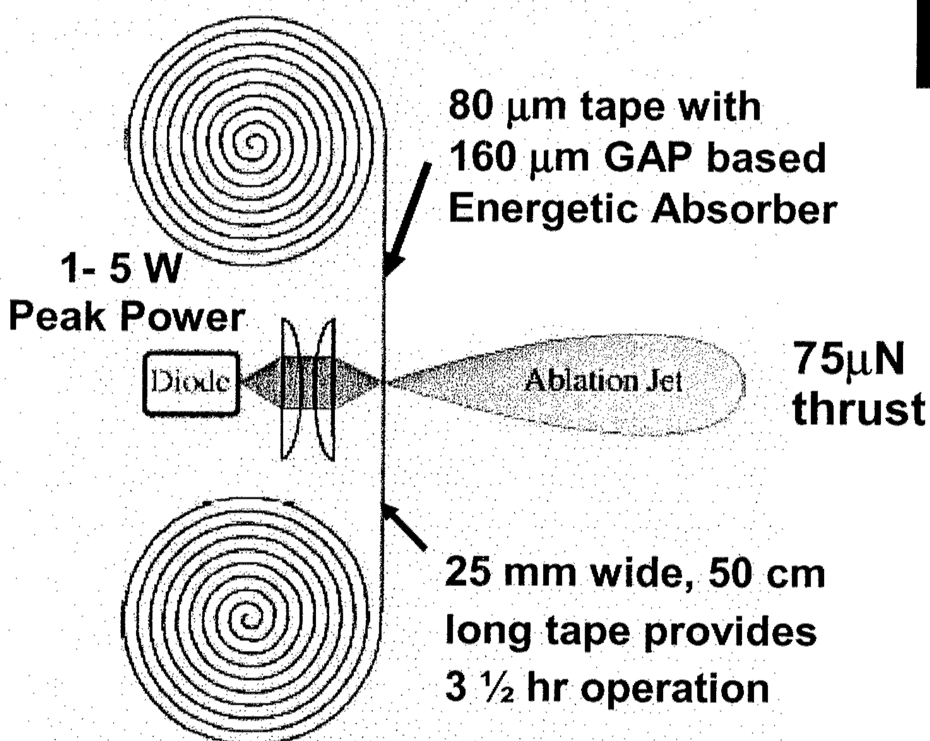
Laser Plasma Thruster (LPT)

Laser-Plasma Thruster

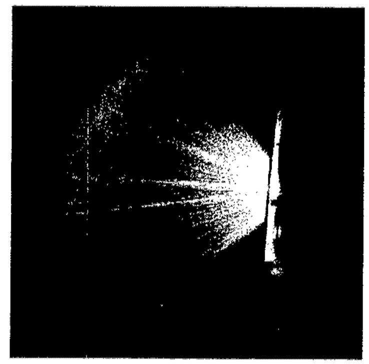
Photonic Assoc. & UNM, AFOSR & AFRL Contracts

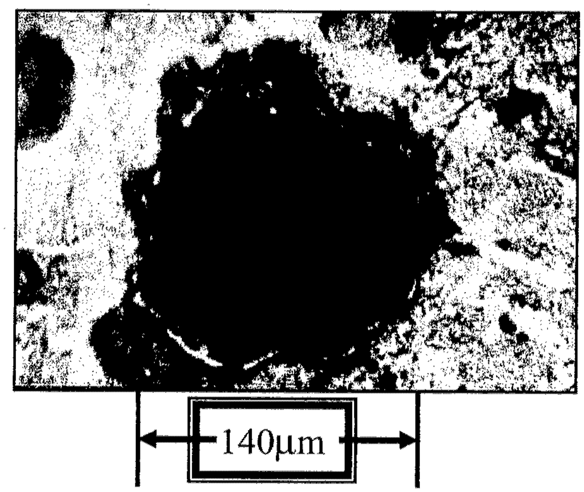
Laser ablation of a solid propellant

- 4 Watt (input) diode laser
  - 3 Volts, 50% efficiency
- T/P = 60 uN/Watt, Isp = 500 s
- Propellant can be any material
  - Low thermal conductance
  - Energetic ablatants



Funding: MDA SBIR Phase I
Tech Monitors: AFRL/PRSS



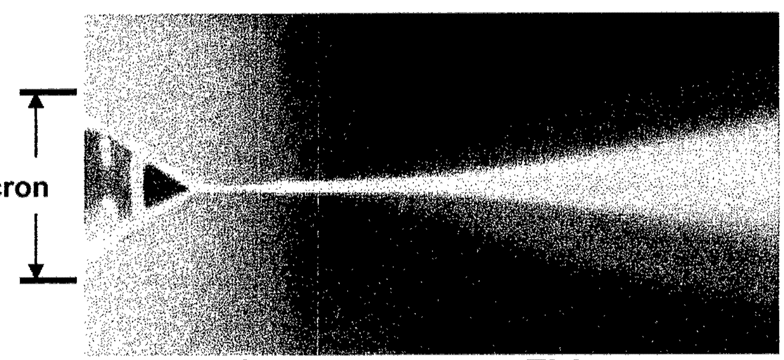


DoD Microsatellite Applications:
- Propulsive ACS
- Fine Pointing/Positioning

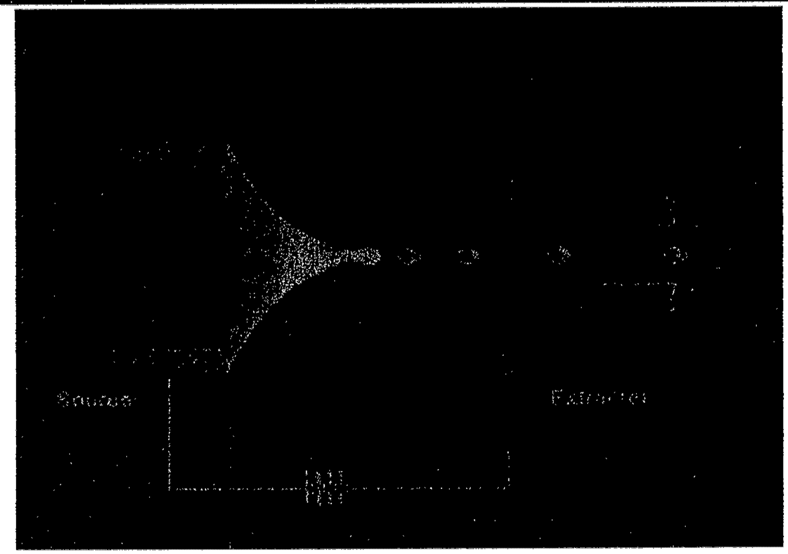
Colloid Thruster

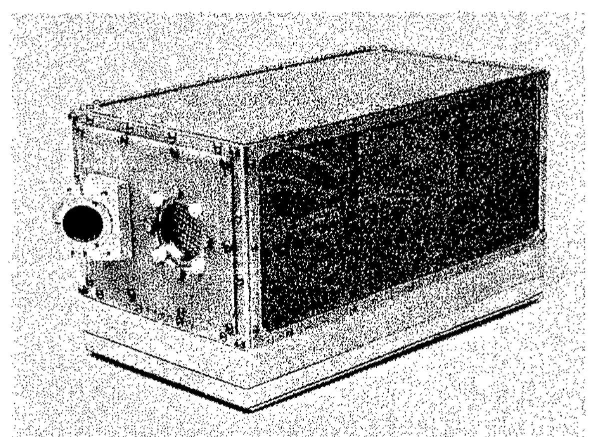
Colloid Thruster

- Electrostatically accelerate charged liquid droplets
- Long heritage (1970s AFRL/TRW)
- Stanford EMERALD flight experiment
- Busek colloid thruster on NASA ST-7
- Ideal propellant characteristics:
  - Very low vapor pressure
  - High electrical conductivity
  - Viscous
- Ionic liquid propellants doubling performance

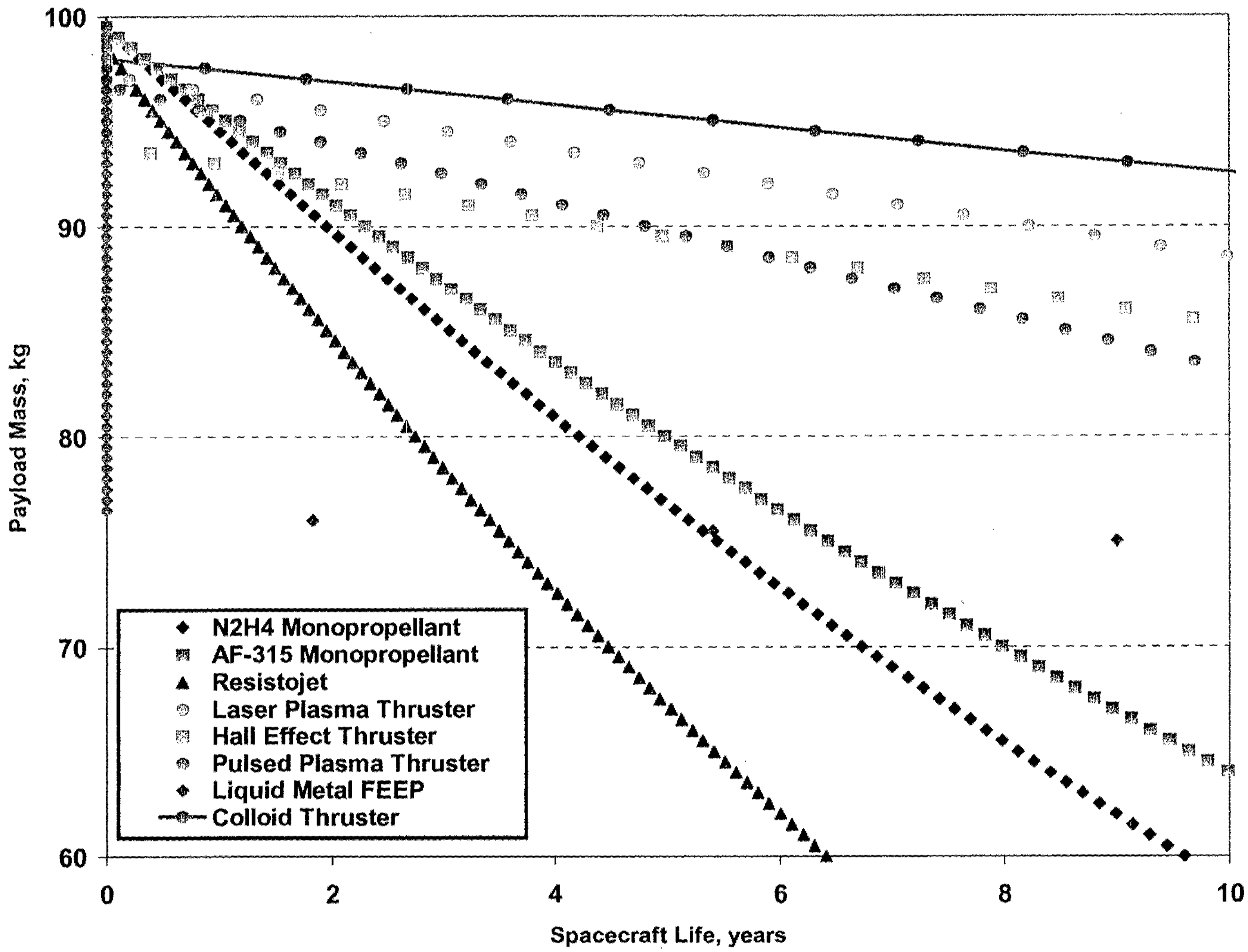


Colloid Thruster Firing


Schematic of thruster operation


Busek ST7 Colloid Thruster Demonstration Model

LEO Formation Flying

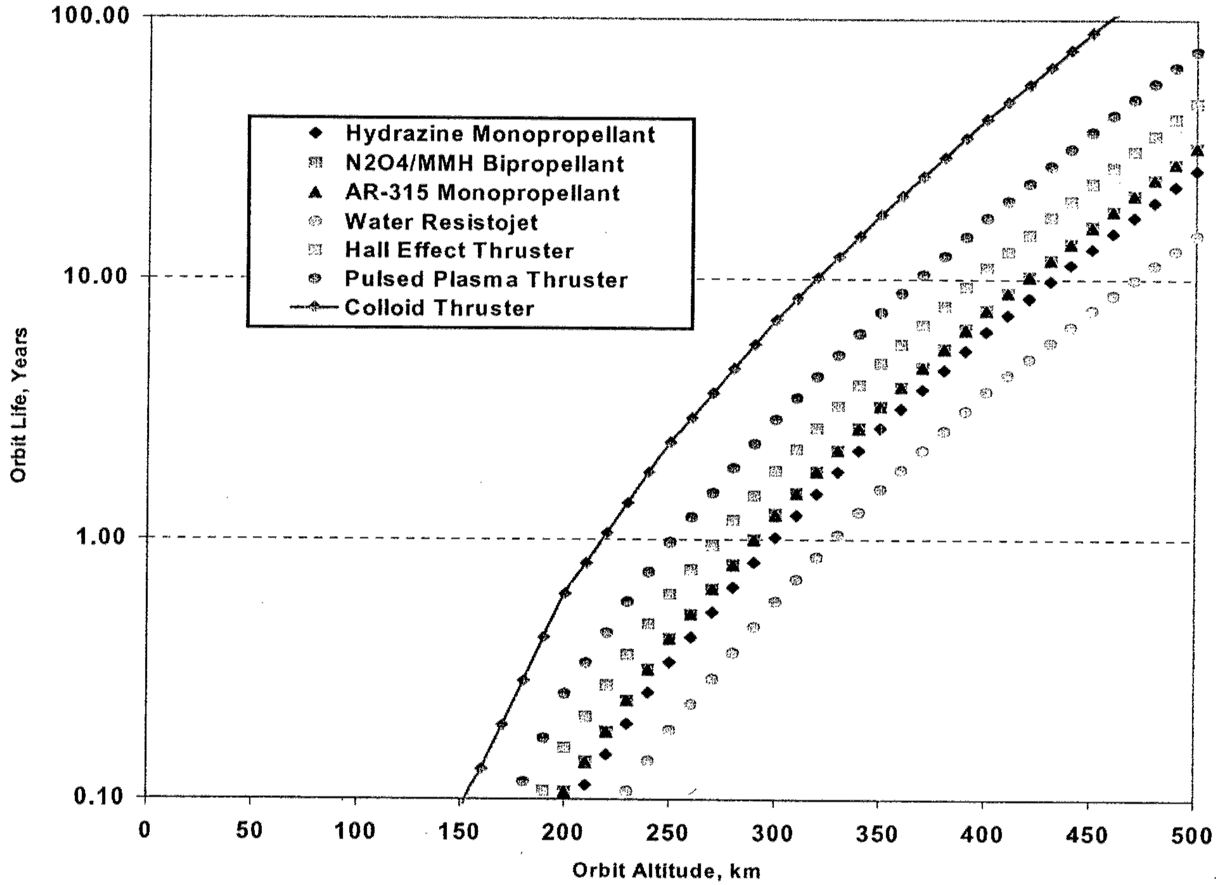


- 100kg Microspacecraft
- 500km Low Earth Orbit
- Multiple spacecraft, ~2.5 km formation
- Stationkeeping required to maintain formation (scaled from TechSat 21 requirements):

  2 mN minimum thrust

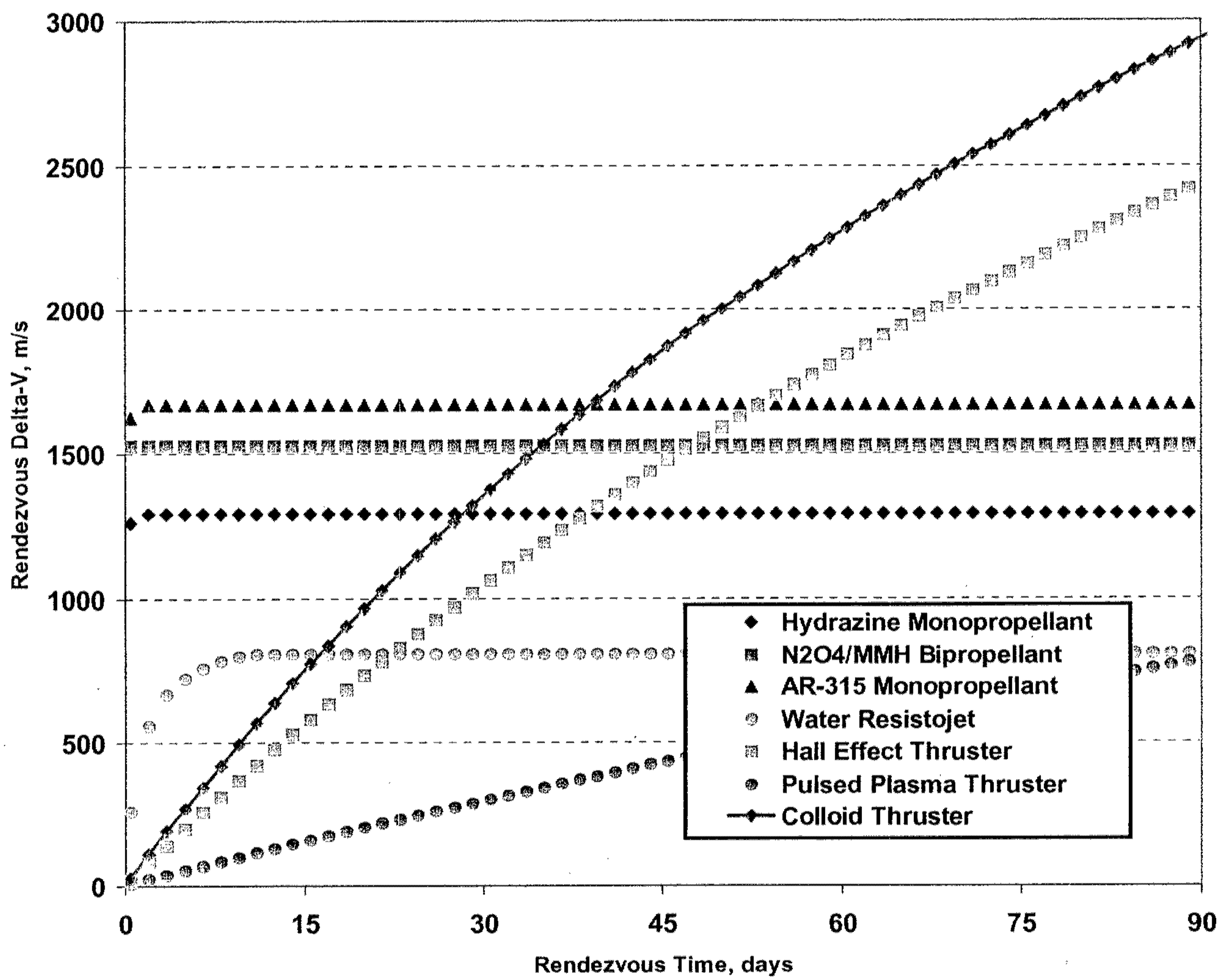
  100 m/s/year total ΔV
- Payload = spacecraft mass minus full propulsion mass

LEO Orbit Life



- 100kg Microspacecraft
- 20kg Propulsion Module
- Low Earth Orbit
- Thrust required to maintain altitude
- Atmospheric drag assumes long-term mean solar flux

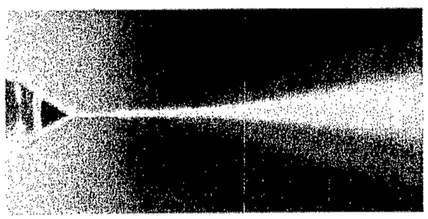
On-Orbit Service and Inspection



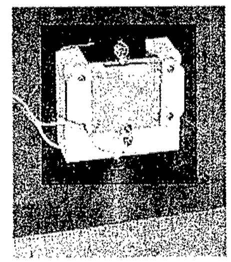
- 100kg Microspacecraft
- 50kg Propulsion Module
- 500km Low Earth Orbit
- Must inspect and/or service friendly spacecraft
- Mission details (target orbit, rendezvous ΔV, allowed time) unknown at launch
- Vehicle must be flexible, trade time vs. ΔV

Colloid Development Needs

Although colloid engines are currently operating well in laboratory environments at thrust levels around 1 μN, thrust levels must increase to the 1 mN range to be useful in DoD missions.



30-micron single emitter (Yale)



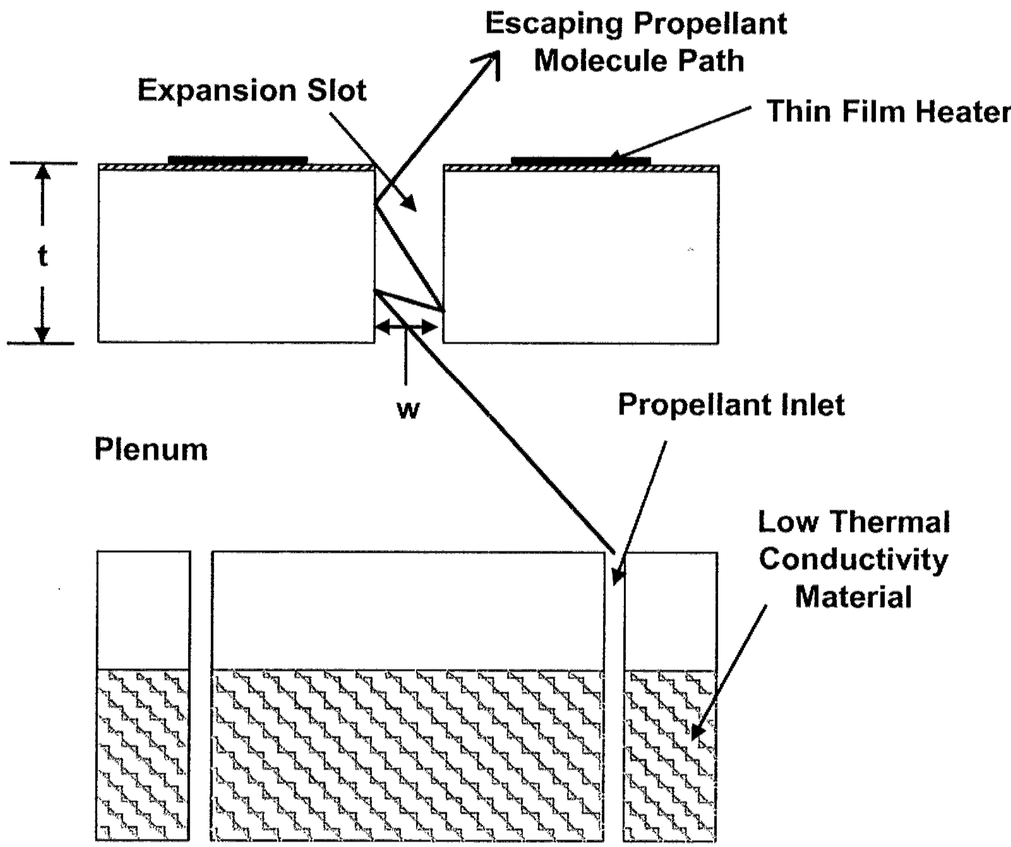
10-cm x 10-cm array (Stanford)

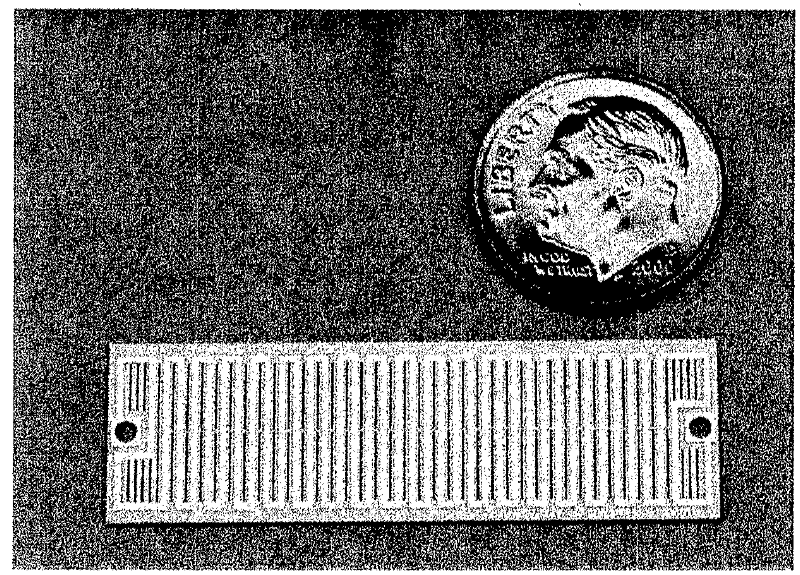
Critical needs to prove the colloid engine concept for primary propulsion onboard 10-kg-class spacecraft within the next 2 years:

1. Accelerate Microfabrication Effort — $400k/year (MIT)
2. Develop/Incorporate Passive Feed Systems (wicking, external wetting) — $150k/year (MIT)
3. Life Testing, Ground Demo — $300k/year (AFRL)
    - Degradation/erosion of emitter
    - Propellant constituency change

Free Molecule Micro Resistojet (FMMR)

MEMS Propulsion: Free Molecule Micro-Resistojet (FMMR)





Concept

- EP design based on systems considerations / limitations
- Systems level performance is key efficiency parameter

US Patent Awarded (No. 6,263,665)

Benefits

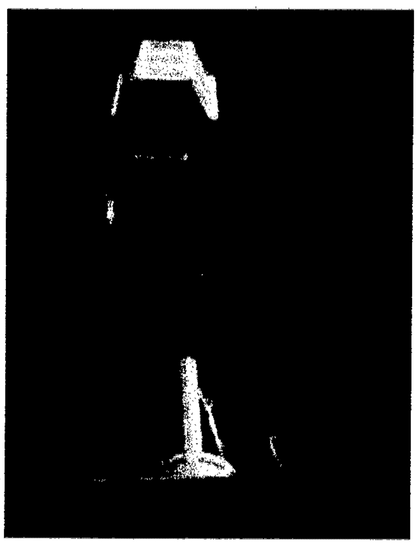
- Low pressure operation
  - Reduces MEMS valve leakage
  - Reduces propellant storage tank mass
- Phase change of propellant
  - Operates on propellant vapor pressure
  - Reduces storage volume
- Reduces likelihood of single point failures
- Permits large range of thrust levels without significant loss in performance

Electrodynamic Tether (EDT)

Electrodynamic Tethers for MicroSats

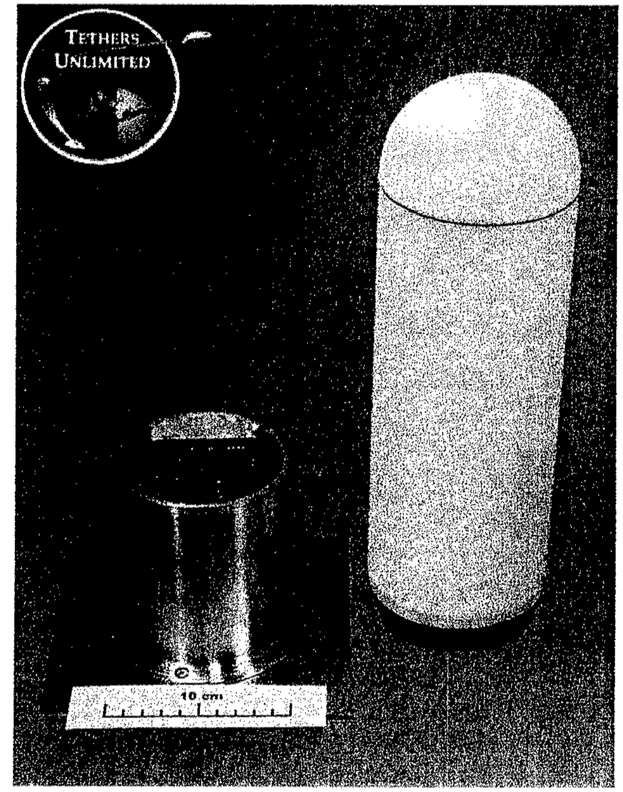
Tethers Unlimited, AFRL Phase II SBIR

- AFRL issued a Phase II SBIR to Tethers Unlimited to design and built an ED tether for deorbiting 100 kg microsatellites
- Deploys 2 km interconnected-multiline conduction tether
- Developed deployment mechanism
- Evaluated several cathodes – selected thermionic device



Deployment Test

- "Barebone" system to deorbit 100 kg microsat has total mass of < 2.5 kg
- More capable system with control of tether dynamics and diagnostics ~ 3.5 kg
- Focusing on power conversion and control for orbit raising applications



The prototype Microsatellite Propellantless Electrodynamic Tether (microPET) avionics and deployer

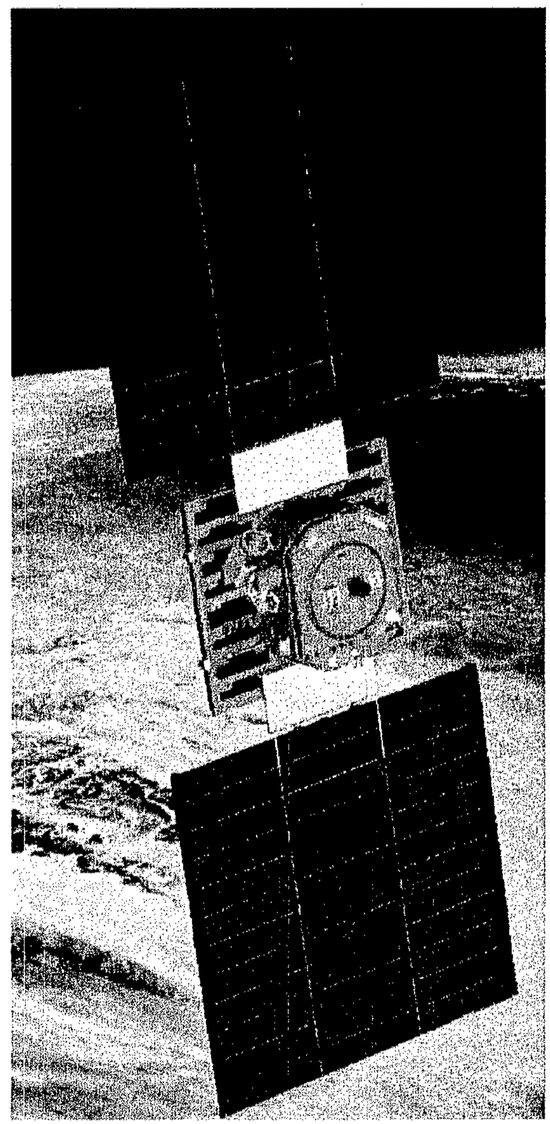
Micro Vacuum Arc Thruster (μVAT)
(see presentation by Juergen Mueller, JPL)

Technology Demonstrators

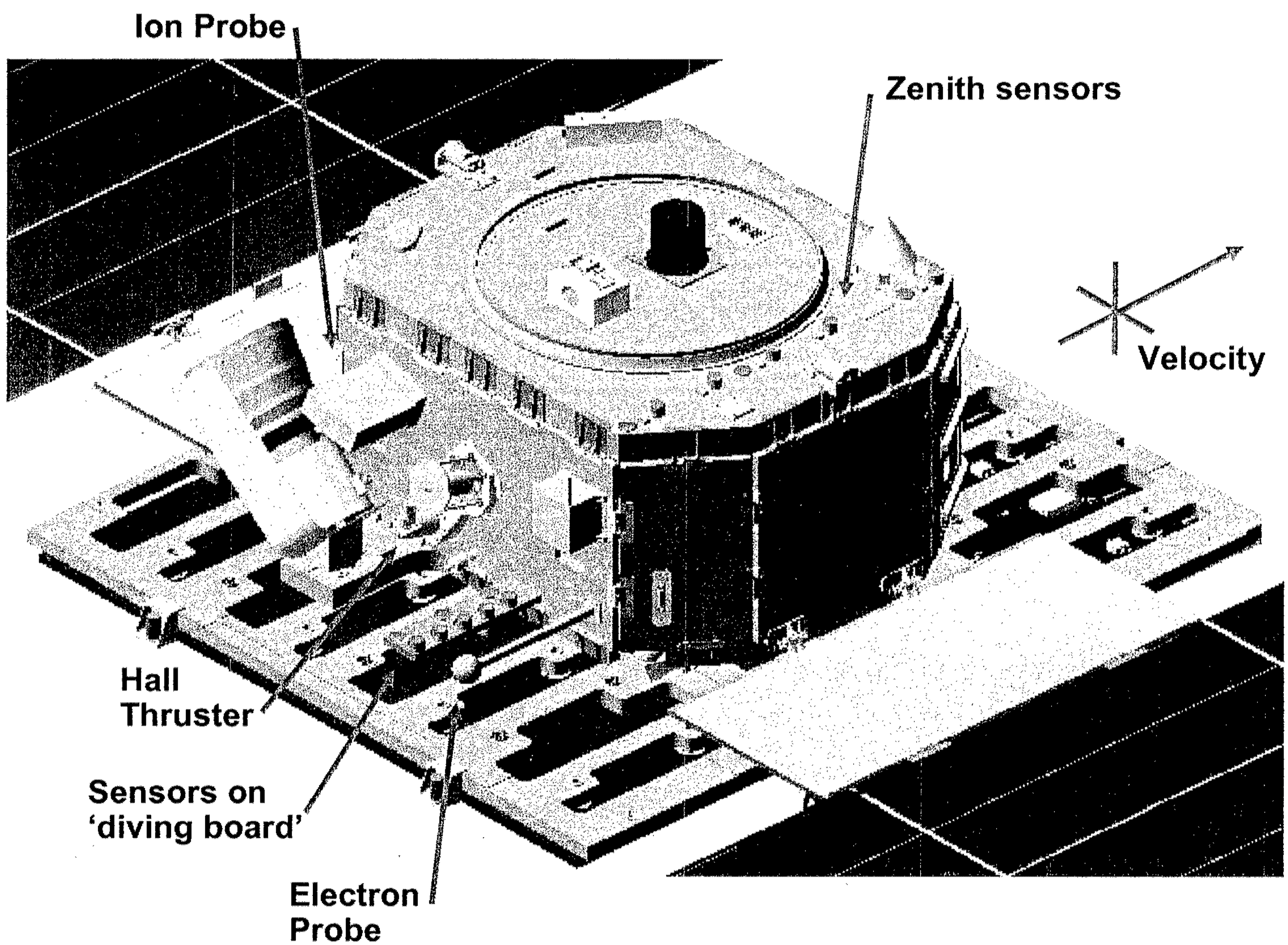
Dr. Andrew Ketsdever
Leader, Non-Equilibrium Flows Group
AFRL/PRSA
Edwards AFB, CA

TechSat 21 Propulsion Instrument Layout

- 3-axis stabilized 150kg spacecraft with significant zenith solar pointing time.
- Ion sensor input 25 cm radial, 75 deg from centerline, pointed at thruster exit.
- Electron sensors: 1 boom mounted, 1 current collector ‘patch.’
- ‘Strip of sensors’ on zenith deck for remote radiometers, photometers, solar cells, current patch.
- ‘Bill-board’ on propulsion panel to allow radiometers, photometers, solar cells to view constant sun.



TechSat 21 Flight Orientation



AFRL XSS-10

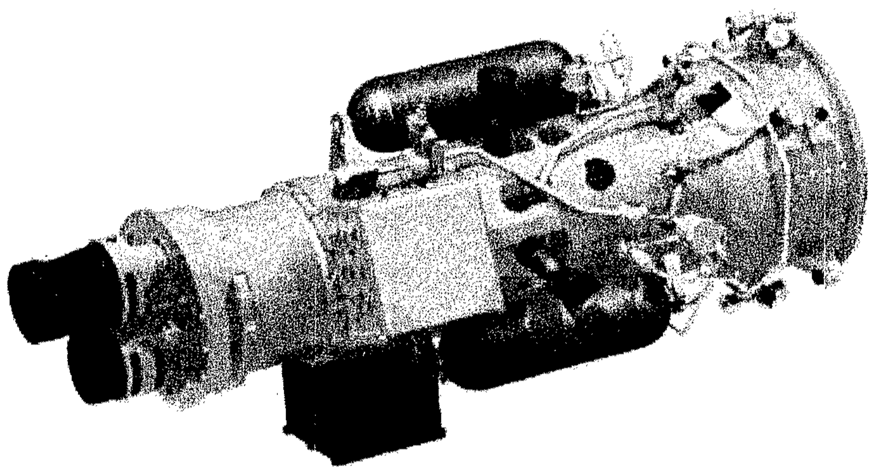
Mass: 28 kg

Contractor: Boeing

Mission: Demonstrate fly-around autonomous inspection of Delta II second stage

Lifetime: 24 hours

Propulsion: Lightweight bipropellant derived from LEAP missile interceptor

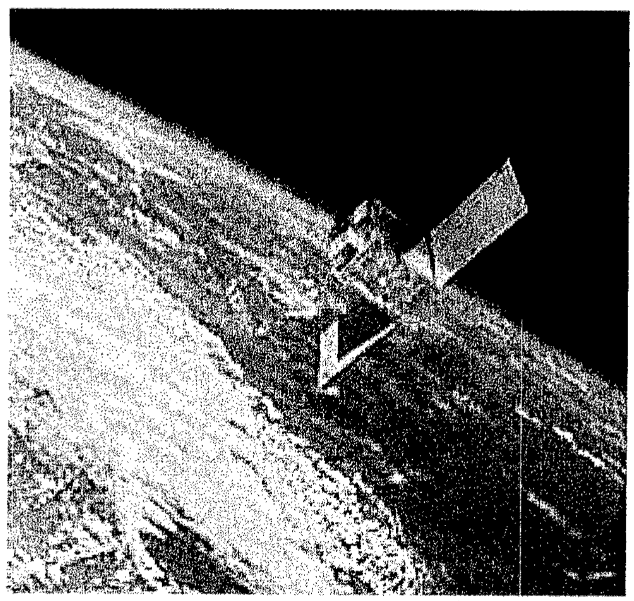


Launched 29 Jan 2003

Mission Success

AFRL XSS-11

Mass:	100 kg
Contractor:	Lockheed-Martin
Mission:	Demonstrate autonomous rendezvous technology
Lifetime:	12-months
Propulsion:	??? for primary
	??? for ACS
	EDT for de-orbit

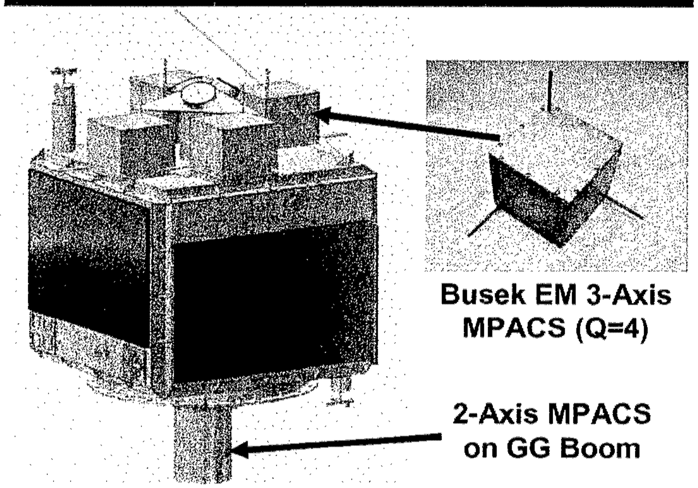


Launch in 2004

MicroPPT Flight HW Development

AFRL/PRSS, Busek, USAFA

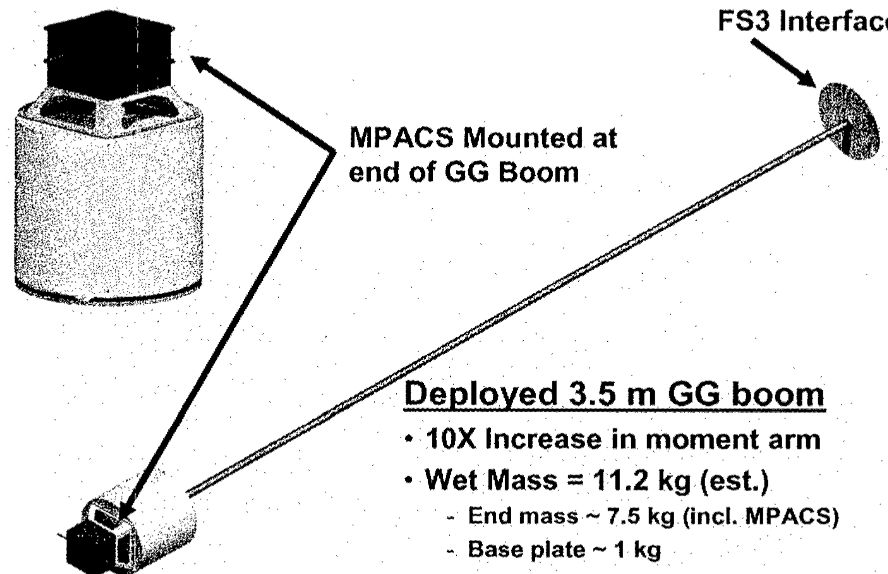
USAF Academy FalconSat 3



AF Mission Need: High I_{SP} Propulsive Attitude Control
- Higher Performance, Lower Mass/Cost than traditional ACS components
- Demonstrate Propulsion on deployed structures

USAFA Flight Demo (FalconSat 3)
- Multi-axis thrusters for ACS
- Thruster deployed at end of GG boom
- Spacecraft systems, payloads monitored for interactions
- 1 Satellite, Launch on MLV-05 (FY06)

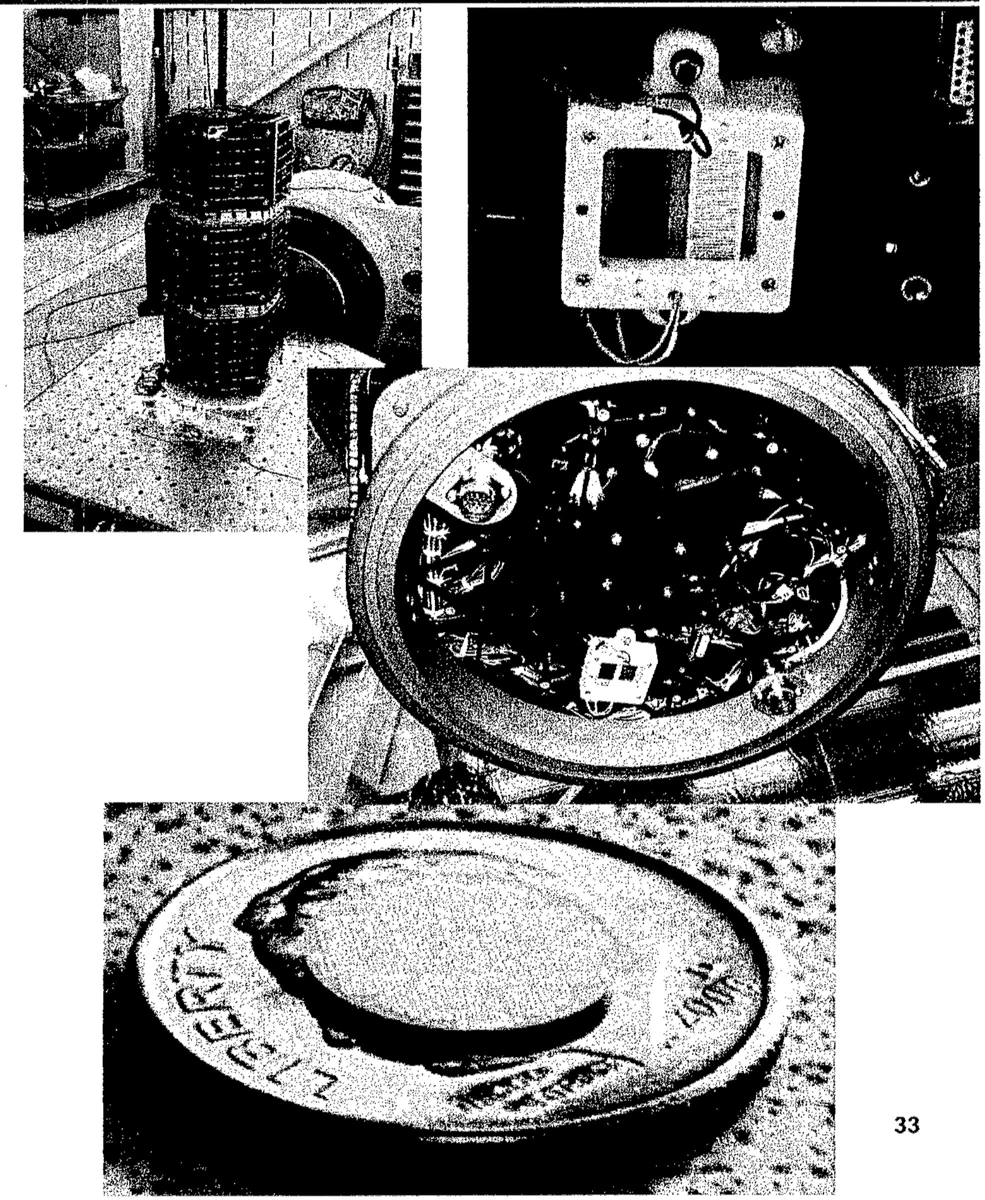
- Micro Propulsion Attitude Control System (MPACS) w/ AFRL MPPT
  - Demonstrates Propulsive ACS and "thruster-on-a-stick"
  - Ranked 18/45 in 02 SERB
  - AFRL product routinely briefed to high level visitors at USAFA
- PR/VS Collaboration for boom dev't
  - MPACS Boom dramatically different than standard GG boom
  - Still in early planning, but will use SBIRs



Deployed 3.5 m GG boom
- 10X Increase in moment arm
- Wet Mass = 11.2 kg (est.)
  - End mass ~ 7.5 kg (incl. MPACS)
  - Base plate ~ 1 kg
- Non-Pyro Actuation
- Shape Memory Composite Hinges

MEMS Propulsion Flight Demos
Free Molecule Micro-Resistojet

- Flight Demonstrations
  - ASU/CU/NMSU Three Corner Sats (Orbital, pending)
    - MEMS heater chip
    - Macro-scale packaging
    - Survivability
      - Launch (Shuttle)
      - LEO Atomic Oxygen
      - Thermal Cycling
  - USC Traveler I (Sub-Orbital, Fall '03)
    - MEMS heater chip
    - MEMS consistent packaging
    - Launch Survivability
  - ASU Nanosatellite III (PROPOSED)
    - Fully integrated MEMS thruster system
    - Orbit raise maneuver (10 km success criteria)

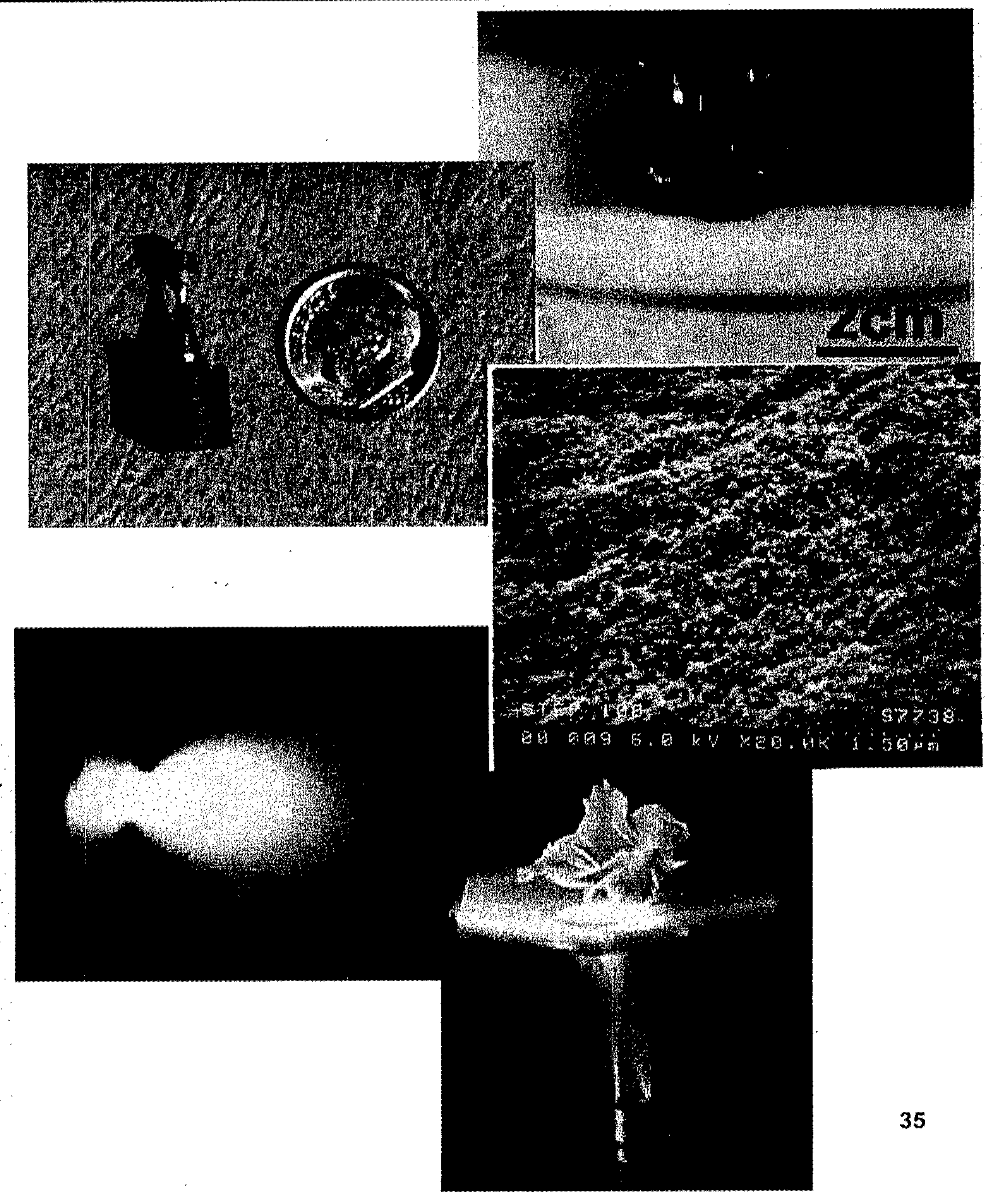


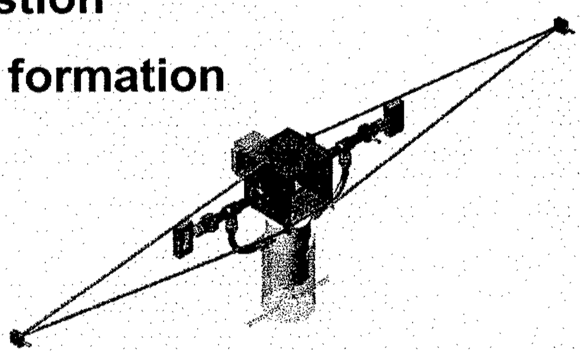
Basic Research Issues

Dr. Andrew Ketsdever
Leader, Non-Equilibrium Flows Group
AFRL/PRSA
Edwards AFB, CA

Microfluidic Technical Areas

- There are several unique aspects of microfluidics research important for micropropulsion
  - Low Reynolds number and rarefied flows*
  - Gas-surface interactions*
  - Modeling and Simulation*
  - Nano-porous media flows*
  - Two-phase flow*
  - Diagnostic development*
  - Combustion*
  - Plasma formation

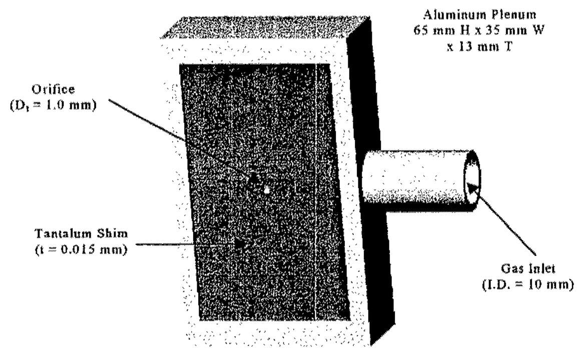


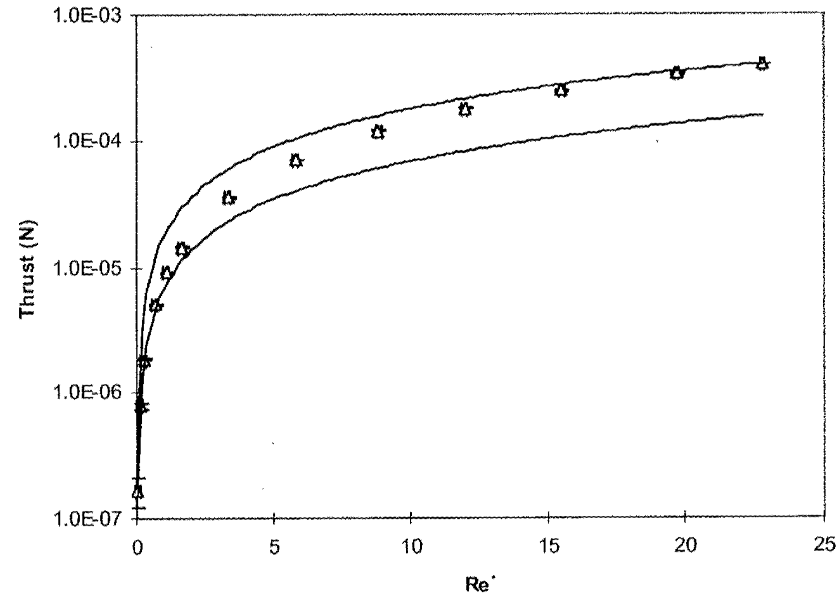


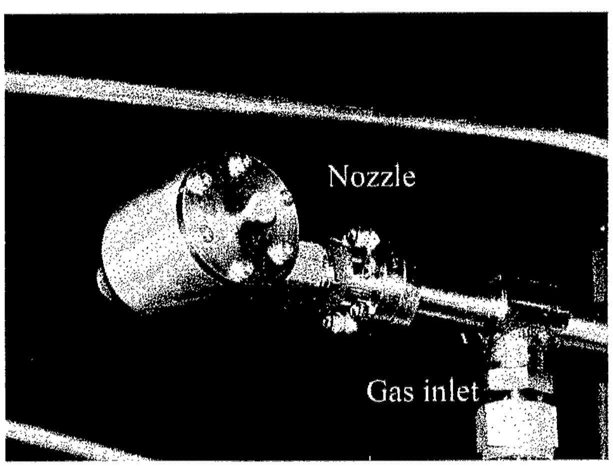
* FY 03 Efforts

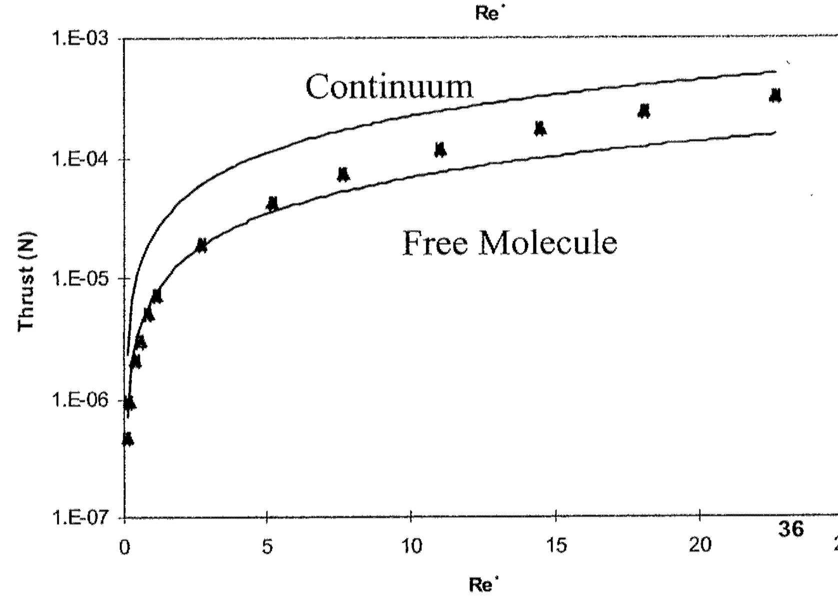
Low Reynolds Number Flow in Micropropulsion Systems

Thrust Comparison Between 1.0 mm Diameter Throat DeLaval Nozzle and a 1.0 mm Diameter Thin Walled Orifice

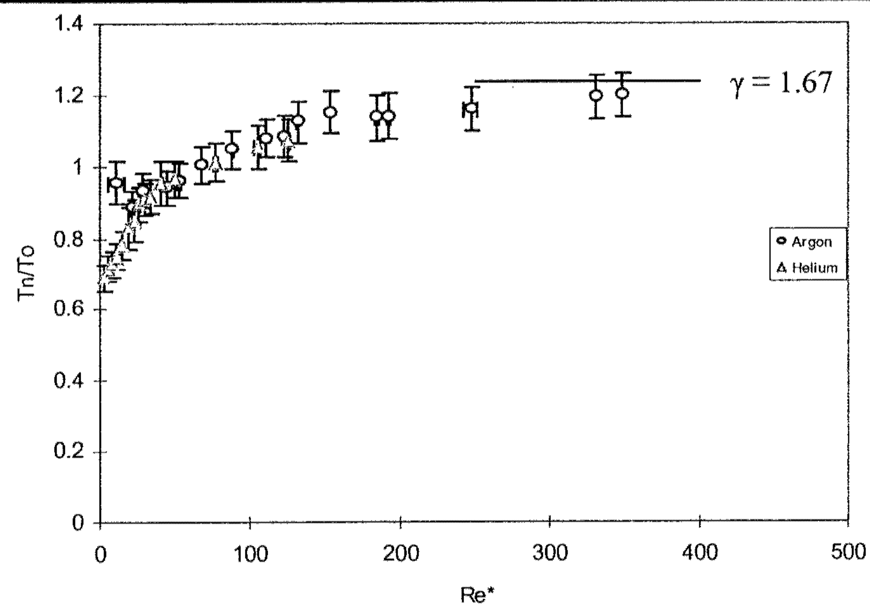




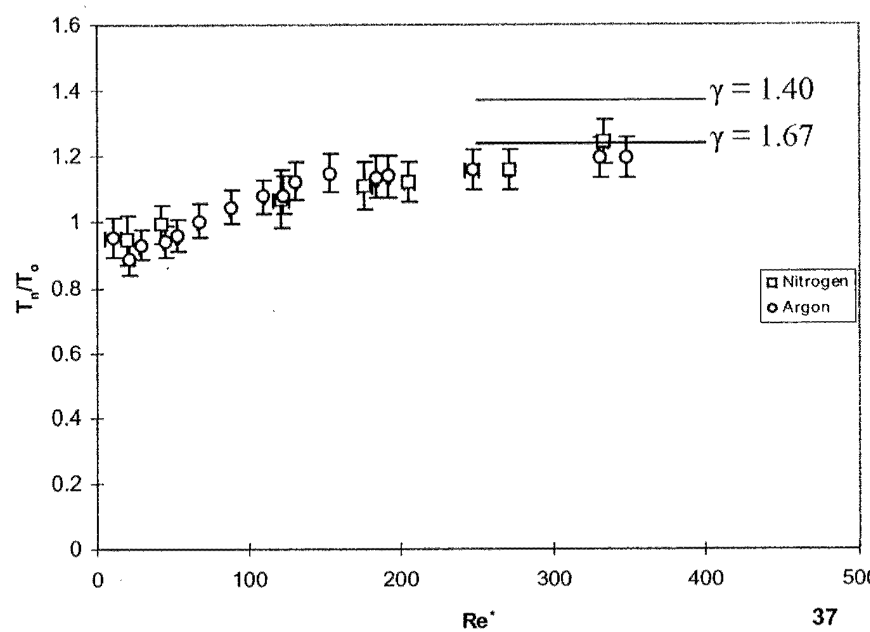




Micronozzle vs. Underexpanded Orifice



- At Re < 70: $T_o > T_n$
- At Re = 70: $T_o = T_n$
- At Re > 70: $T_n > T_o$



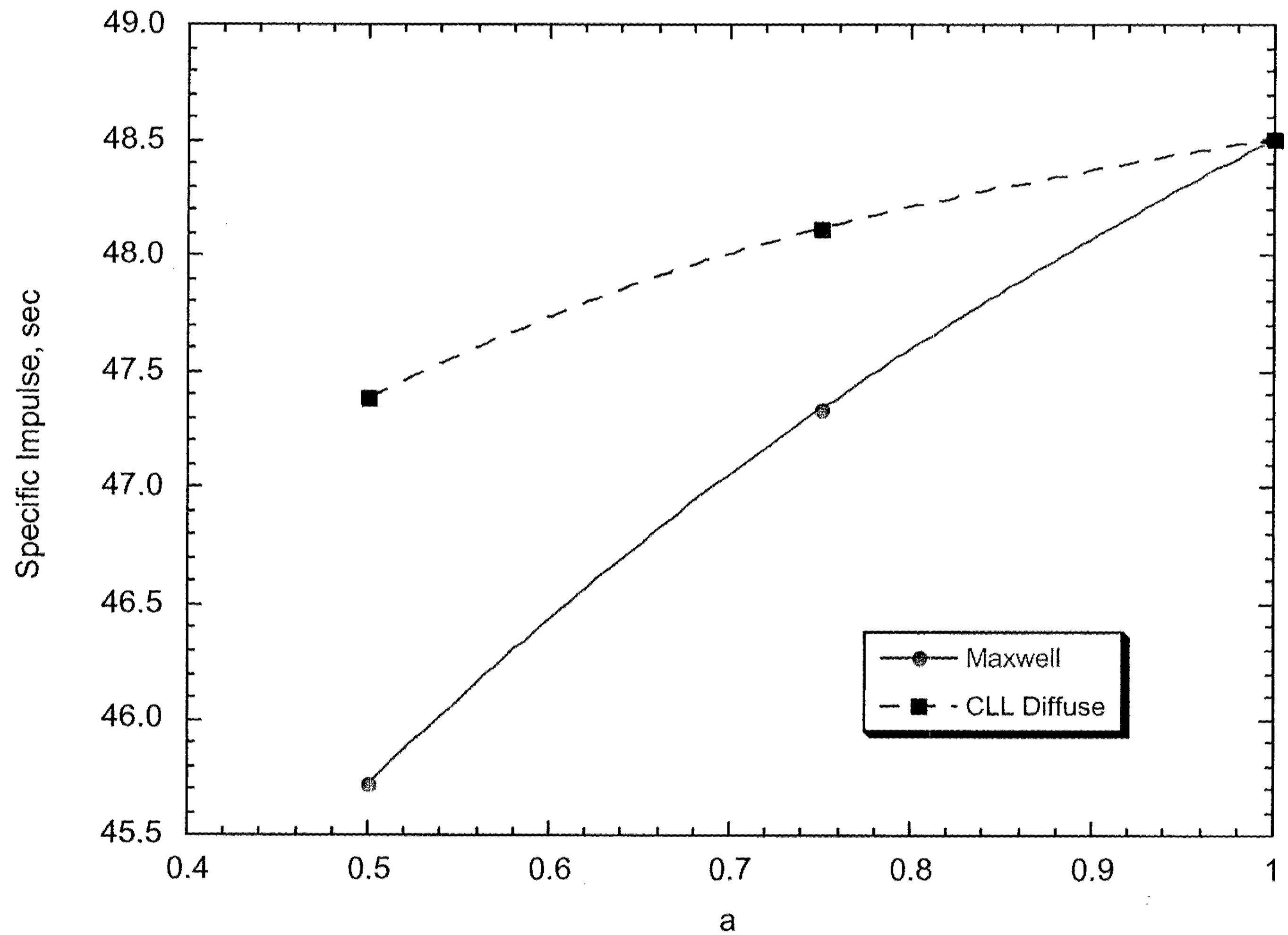
- Argon and helium data transitioning to continuum flow ratio for monatomic gases
- Nitrogen data lagging in transition to continuum flow ratio (internal energy losses?)

Microfluidics Research
Gas-Surface Interactions

- Surface area to volume ratio increases as the flow scale decreases
  - Molecules can interact with surfaces more than with other molecules in the flow
  - Several types of micropropulsion systems are driven by propellant molecules interacting with surfaces at elevated temperature (e.g. resistojets)
  - Energy accommodation and losses at the walls is a driving factor in micropropulsion system efficiency
- Detailed physical description of GSI is necessary
  - Determining performance
  - Maximizing efficiency
- For FMMR, surface molecule vibrational energy (high surface temperature) is converted into propellant molecule kinetic energy
  - How efficiently?
  - M&S used to parameterize the flow (Direct Simulation Monte Carlo)

Gas-Surface Interactions FMMR Results

Direct Simulation Monte Carlo M&S Results



Argon Propellant

Kn ~ 1

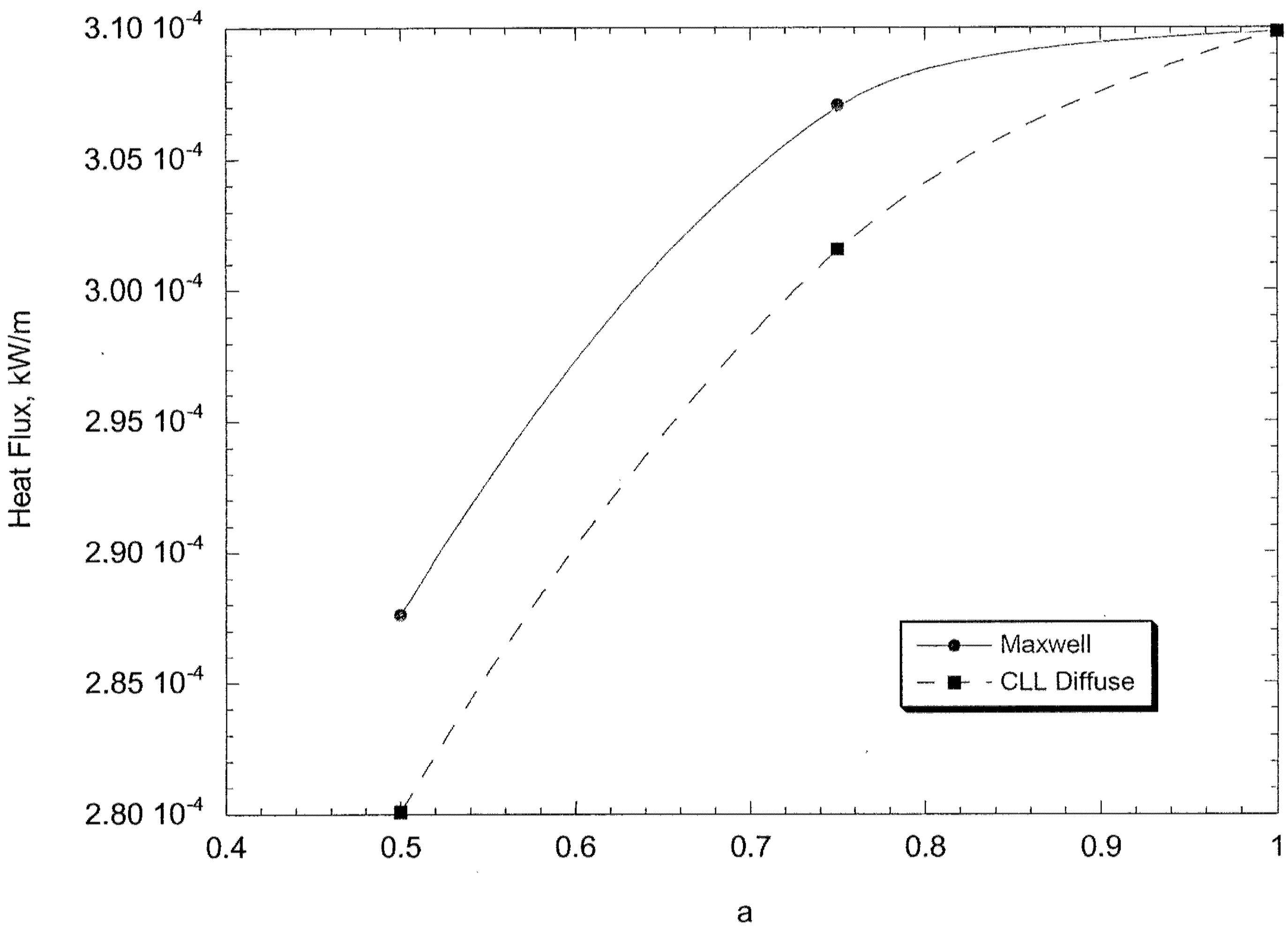
P_o = 50 Pa

T_w = 600 K

100 μm Slot

Gas-Surface Interactions
FMMR Results

Direct Simulation Monte Carlo M&S Results



Argon Propellant

Kn ~ 1

P_o = 50 Pa

T_w = 600 K

100 μm Slot

Infrastructure Issues

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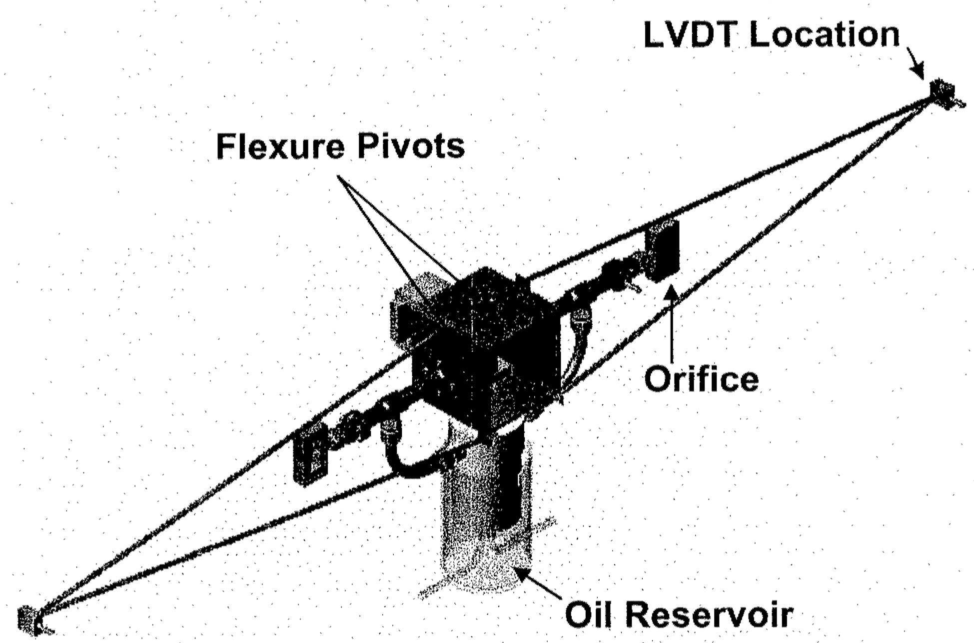
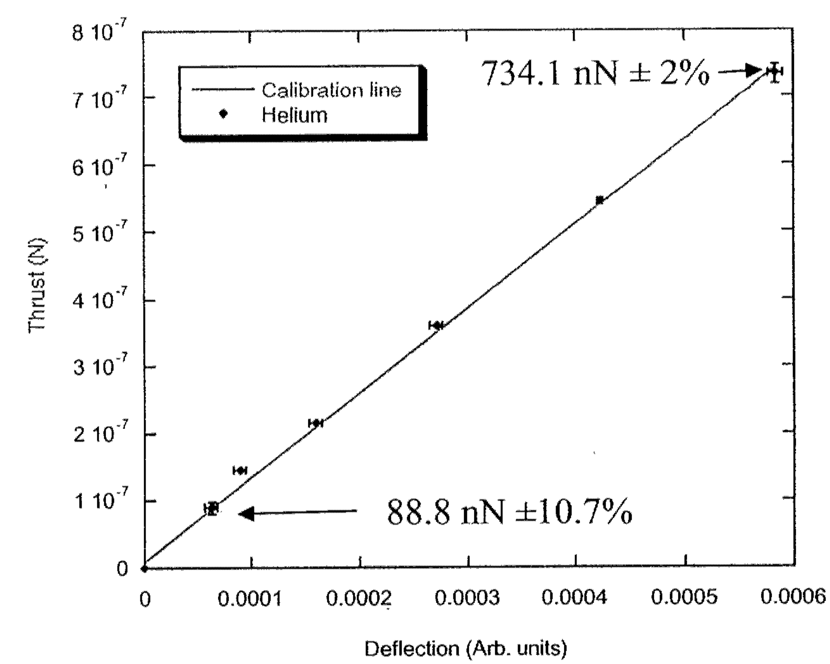
Nano-Newton Thrust Stand

- Thrust levels down to 88 nano-Newtons accurately measured
- Impulse measurements down to 100 nN-sec accurately measured
- Gas Dynamic Calibration Technique validated for low thrust measurements

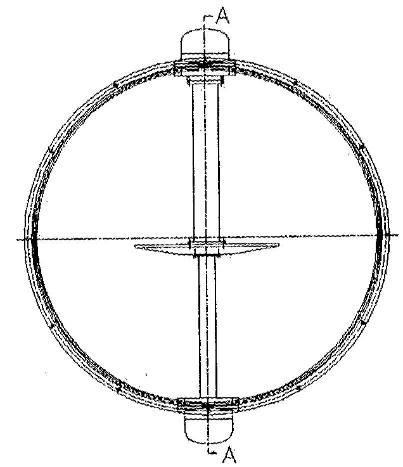


Symmetric about center of rotation

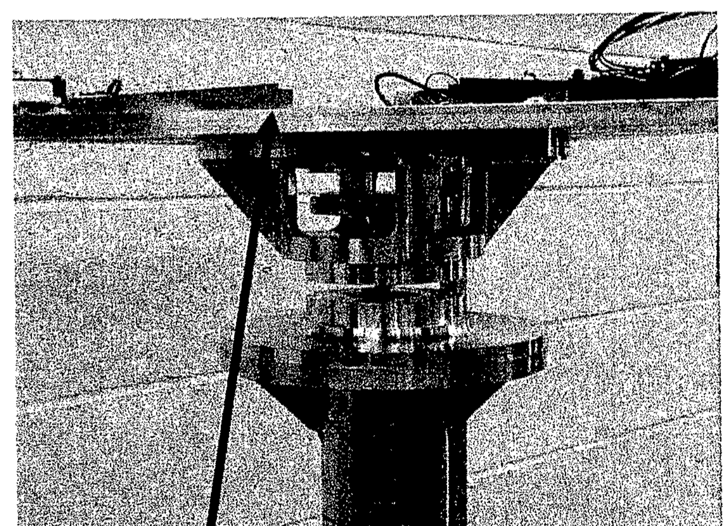


Magnetic Levitation Thrust Stand

- AFRL issued a Phase II SBIR to Busek Co. to develop and deliver a thrust stand capable of resolving 0.1 μN forces
- Movable portion of thrust stand is magnetically suspended (Maglev)
- Capable of supporting 30 kg thruster system mass
- Reduces facility vibration effects and allows frictionless rotation
- Two modes
  - Force Nulling (Steady state thrusters)
  - Free Rotation (Pulsed thrusters)
- First prototype demonstrated
- Second demonstration with colloid and μPPT thrusters planned for Aug 03
- Delivery date: Nov 03



Maglev Installed in Vacuum Tank



Maglev Platform

BUSEK

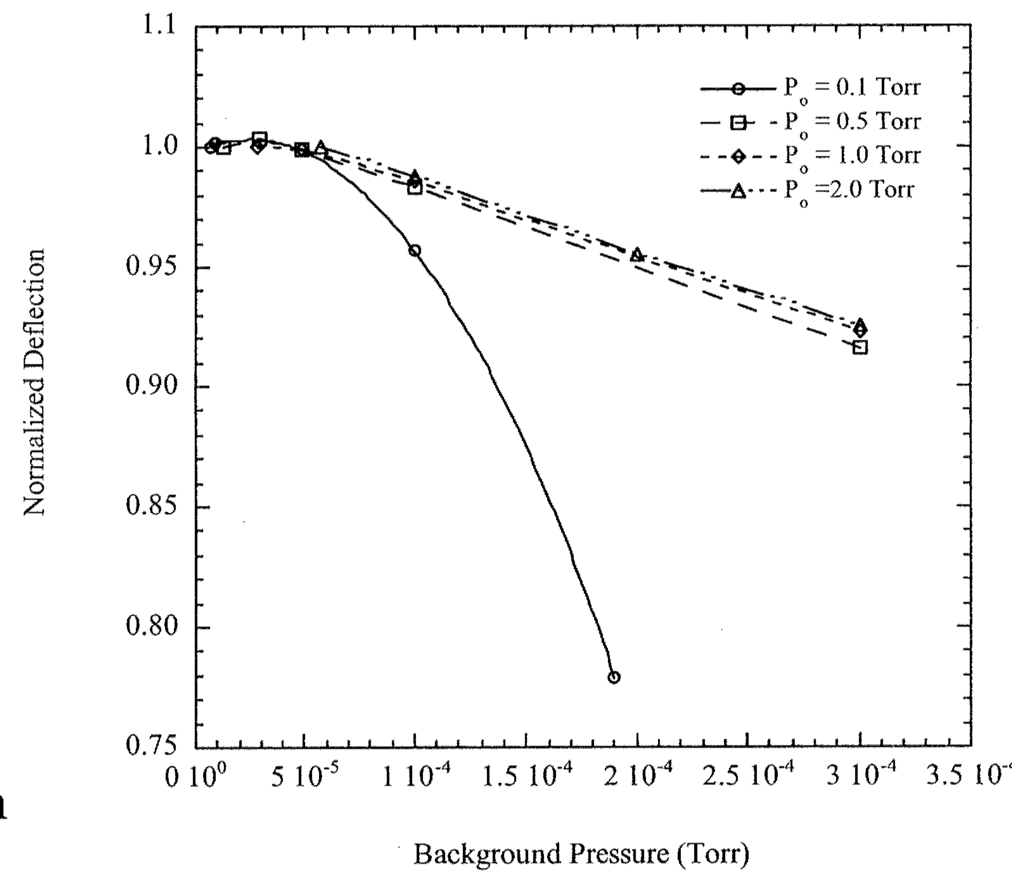
Facility Effects on Micropropulsion Thrust Measurements

- Measured deflection asymptotes at lower facility background pressures
→ pressures below 10^{-5} Torr required for microproulsion system performance measurements

- Serious implications may exist for micropropulsion test facilities

- Simple scaling of facility pumping system may not be adequate

- First facility effects measurements in the thrust range below 0.5 mN



Normalized deflection for nitrogen as a function of facility background pressure